Influence of Pecan Biochar on Physical Properties of a Norfolk Loamy Sand

Warren J. Busscher,[1] Jeff M. Novak,[1] Dean E. Evans,[1] Don W. Watts,[1] M. A. S. Niandou,[2] and Mohamed Ahmedna[2]

Abstract: Because the southeastern US Coastal Plain has high temperatures and abundant rainfall, its sandy soils have poor physical characteristics and low carbon (C) contents. To increase soil C, we added switchgrass (*Panicum virgatum*) and nonactivated recalcitrant pecan biochar. Biochar was developed by pyrolyzing ground pecan shells at 700 °C. Biochar had 88% C, 0.4% N (C:N ratio, 220:1); 58% of its C resided in polymerized aromatic ring structures. Biochar treatments were 0, 5, 10, or 20 g kg^{-1} of soil, which was the Ap horizon of a Norfolk loamy sand, a thermic Typic Kandiudult. Switchgrass was ground to a fine powder and added to the biochar treatments at rates of 0 or 10 g kg^{-1}. Treatments were incubated in 750-g columns for 70 days at 10% (wt wt^{-1}) water content. Biochar decreased soil penetration resistance; adding switchgrass also decreased it by the end of the experiment. Biochar and switchgrass affected aggregation, infiltration, and water-holding capacity; but results were mixed. Although the nonactivated biochar (and switchgrass) improved some soil physical characteristics, other biochar formulations may have more of an effect on soil properties.

Key words: Gracenet, pyrolysis, Coastal Plains, penetration resistance, biochar, charcoal.

(*Soil Sci* 2010;175: 10–14)

It has long been known that organic matter (OM) additions improve soil tilth (Waksman, 1937) and reduce strength (Free et al., 1947), even for hard layers of loamy sands such as those found in the southeastern US Coastal Plain (Ekwue and Stone, 1995). Unfortunately, in the southeastern United States, soil OM does not necessarily increase from year to year with the addition of residues from row crops because it rapidly oxidizes in the subtropical environment (Parton et al., 1987; Wang et al., 2000). Research has shown that OM increased more for noninversion tillage systems that left crop residues on the surface than for tillage systems that mixed it into the profile, but the increase was only in the top few centimeters (Hunt et al., 1996; Novak et al., 2007). As a result, southeastern US Coastal Plain soils have low OM contents, leading to low carbon (C), little aggregation, and reduced infiltration.

Because OM does not build up to soften the soil and because the hardest layer is below the plow layer, producers typically till these sandy Coastal soils with subsoiling, a noninversion method of deep tillage. Deep tillage loosens the soil to allow root growth into deeper horizons, where soil structure permits root development and water retention (Adeoye and Mohamed-Saleem, 1990; Akinci et al., 2004). However, as fuel prices increase, deep tillage becomes prohibitively expensive because it requires 20 to 25 L of fuel ha^{-1} (Karlen et al., 1991). Deep tillage becomes a significant part of plant production management costs, and its effect is temporary (Carter et al., 1996; Busscher et al., 2000). Over time, the loosening effect of tillage diminishes as the E horizon (just below the Ap) reconsolidates (Raper et al., 2000), reducing yields (Lapen et al., 2001). Yields are reduced by incomplete reconsolidation from one growing season to the next that increases soil strength enough to restrict root growth.

Rather than continue to till these soils, it would be better for them, for the economy, and for the environment (Laird, 2008) if C could remain in the soils. Organic C could improve soil physical and chemical properties; it could also beneficially sequester C (Busscher et al., 2007). One type of C that may satisfy both the soil's need for C and the environment's need to sequester C would be biochar or charcoal. Carbon in this form resists degradation (Steiner et al., 2007), having remained in tropical Amazonian soils for centuries (Mann, 2005). It is expected to improve soil physical and chemical properties (Laird, 2008) depending on the properties of the added C. Our hypothesis was that increasing soil C through the use of nonactivated biochar would improve soil physical properties.

MATERIALS AND METHODS

Biochar and Soil

Biochar used in the experiment was made from pecan (*Carya illinoinensis*) shells that were ground to pass through a 2-mm sieve using a Retsch Mixer Mill (SR-2000, Cole-Palmer, Vernon Hills, IL). Ground shells were poured in a crucible that was placed into a Lindberg box programmable furnace (model 5116HR, Lindberg, Watertown, WI) equipped with an air-tight retort that was purged with N_2 at a flow rate of 0.1 m^3 h^{-1}. The furnace was controlled by a multiple-step temperature controller that heated the pecan shells to 40 °C, increased the temperature up to 170 °C at a rate of 5 °C min^{-1}, and maintained them at 170 °C for 30 min. The controller then increased the temperature to 700 °C at a rate of 5 °C min^{-1}. At this point, the ground pecan shells were pyrolyzed for 1 h, producing the biochar. The oven temperature was reduced, allowing the biochar to cool overnight in the N_2 atmosphere. After cooling, the biochar was ground to pass through a 0.6-mm sieve. The pH of the biochar was 7.49; its ash content was 3.8%. The biochar had 88% C, 0.4% N (C:N ratio, 220:1); 58% of its C resided in polymerized aromatic ring structures. These characteristics were determined by Novak et al. (2009a) using spectrographic analysis.

Soil used in the experiment was the Ap horizon of a Norfolk loamy sand, a fine-loamy, siliceous, thermic Typic Kandiudult. It was collected from the edge of a 2-ha soybean research field 2 km northwest of Florence, South Carolina (N 34.24109 W 79.81322). When collected, the soil was near field capacity. It was removed from the field and pushed through a 10-mm sieve to remove debris. It was then air-dried and pressed through a 2-mm sieve. The soil was massive in structure, abraded easily, and was difficult to penetrate when dry (Busscher et al., 2000).

[1]USDA-ARS, Florence, SC. Dr. Warren J. Busscher is corresponding author. E-mail: warren.busscher@ars.usda.gov
[2]North Carolina A&T State University, Greensboro, NC.
Received August 14, 2009, and in revised form November 17, 2009.
Accepted for publication November 18, 2009.

ISSN: 0038-075X
DOI: 10.1097/SS.0b013e3181cb7f46

Norfolk loamy sand formed in Coastal Plain marine sediments; it was well drained with 1.2- to 1.8-m-deep seasonally high water tables. Over the years, the Ap horizon had been tilled to a depth of about 0.20 m. Below the plow layer, the soil had an eluviated E horizon that restricted root growth. The E horizon typically extended to depths of 0.30 to 0.45 m; it overlaid a sandy clay loam Bt horizon that extended beyond the 0.6-m depth. The Ap horizon had 1 to 3 cmol kg^{-1} cation exchange capacity, 20 to 80 g kg^{-1} clay, and 2 to 20 g kg^{-1} OM (Soil Survey Staff, 2006). Soil texture of the Ap horizon was 71.2% sand, 26.5% silt, 2.4% clay measured using the method of Miller and Miller (1987); its OM content was 6.6 g kg^{-1} measured on a LECO LN2000 (LECO Corp, St Joseph, MI).

Treatments and Column Preparation

Eight soil-amended treatments included all combinations of 750 g of air-dried soil mixed with 0 g kg^{-1} or 10 g kg^{-1} switchgrass that had been ground to pass a 6-mm sieve in a Wiley Mill (Arthur Thomas, Co, Philadelphia, PA) and 0 g kg^{-1}, 5 g kg^{-1}, 10 g kg^{-1}, or 20 g kg^{-1} pecan shell biochar. Using a standard acre furrow slice, these rates approximate switchgrass field applications of 0 or 22 tonnes ha^{-1} and biochar applications of 0, 11, 22, or 44 tonnes ha^{-1}. Treatments were replicated three times.

The biochar incubation experiment was conducted in open-top, 10-cm-diameter, 17-cm tall, schedule-40 PVC columns. Column bottoms were sealed using 20-mesh nylon screens to support the soil. Soil was mixed with water in a twin shell dry blender (Patterson-Kelley Co, Inc, East Stroudsburg, PA) for 15 min to obtain a moisture content of 10% (wt wt^{-1}), representing the field capacity of the Norfolk Ap horizon. Soil was hand mixed with biochar and switchgrass to obtain the treatments. Treated soil was poured into columns as they were tapped on a laboratory bench to obtain an initial bulk density of 1.2 g cm^{-3}; this created a freeboard above the soil surface of approximately 9 cm depth. The 1.2-g cm^{-3} bulk density was chosen because it was a relatively loose soil that would typically compact in the field; presumably the amendments would affect compaction. Treatments were maintained at 10% soil water contents on a dry weight basis by weighing and adding water to the columns two to three times a week. Treatments were laboratory incubated for 70 days at 10% soil moisture content at room temperatures ranging from 17 °C to 27 °C and relative humidities ranging from 23% to 61%.

Measurements

At 28 and 70 days after the beginning of the experiment, treatments were leached with 1.6 pore volumes of deionized water (450 mL, based on the initial bulk density). Leaching was performed by pouring the water into the freeboard above the soil and letting the head drop as the water infiltrated into the soil. After the water finished draining through the soil, treatments were covered and allowed to come to equilibrium. Arriving at equilibrium took 2 to 4 weeks; the variable time was caused by the different treatment effects and differences of drying times in the laboratory after the two leaching dates. Once treatments were at equilibrium, penetration resistance (PR) measurements were taken to determine soil strength. Penetration resistance was measured at 44 and 96 days after the beginning of the experiment on the soil surface with a 3-mm-diameter, stainless-steel, flat-tipped probe. The probe was attached to a strain gauge and a motor geared to penetrate the soil at a rate of 0.28 mm s^{-1} to a depth of 5 mm. Strain gauge output was expressed in millivolts and read at a rate of 100 Hz on a CT-23X Micrologger (Campbell Scientific, Inc, Logan, UT) and subsequently uploaded to a computer for analysis. After probing to 3- to 5-mm depth, PR output either reached a plateau or peaked. In either case, the mean of the top 10 values was used as the PR reading. Three probings were taken on the soil surface halfway from the center to the edge of the pot at equally spaced positions around the circumference; data for these three probings were averaged and treated as a single data point (Busscher et al., 2000).

At the end of the incubation period and after probe resistance readings, at 97 days, soils were removed from containers and representative subsamples of approximately 250 g were taken for aggregate analysis. Aggregate sizes were measured by sieving the subsample through a 4-mm screen and placing it into a nest of sieves with openings 2 mm, 1 mm, 0.5 mm, and 0.25 mm and shaking the nest with an Octagon Digital Sieve Shaker (Endecotts, Inc, London) that ran at a rate of 60 Hz with amplitude of approximately 3 mm for 1 min using the procedure of Sainju et al. (2003). Aggregation amount was calculated as the percent of the sample retained on the sieves that was not an individual particle.

Data Analysis

Data were analyzed using analysis of variance and least significant difference mean separation procedure (SAS Institute Inc, 2000). Data were tested for significant differences at $P = 0.05$ level of significance unless stated otherwise.

RESULTS AND DISCUSSION

Penetration Resistance

Penetration resistances were measured at 10% water content. Water content equilibration was important because we wanted to measure the differences among amended treatments without complications caused by dryer soils that would be harder or wetter soils that would be softer. After averaging over replicates, water contents for the 2 days of PR measurements ranged from 0.098 to 0.10 g g^{-1} at 44 days and from 0.091 to 0.10 g g^{-1} at 96 days, with no significant differences among treatments or interactions or between days of measurement. Water contents were considered to not have an effect on penetrometer readings.

When PR were compared in the analysis of variance, they were significantly different for both switchgrass and biochar amendments, but their interaction was not significantly different. Treatments with switchgrass added were only statistically significantly lower for the second date of readings (0.92 MPa vs. 0.99 MPa with least significant difference [LSD] [0.05] 0.14 at 44 days and 0.97 MPa vs. 1.10 MPa with LSD [0.05] 0.13 at 96 days). Although the switchgrass reduced PR, its effect would

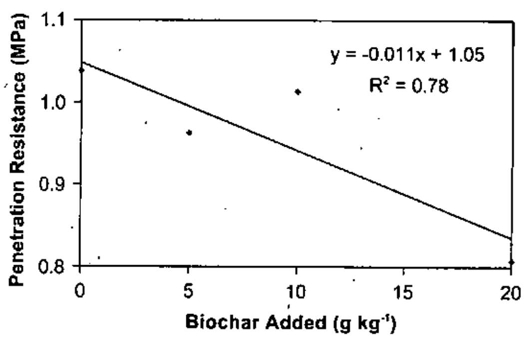

FIG. 1. Plot of soil strength for various levels of biochar after 44 days of incubation.

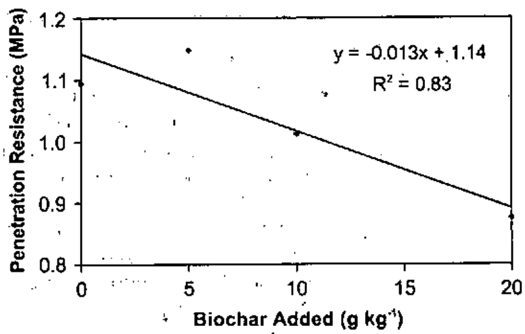

FIG. 2. Plot of soil strength for various levels of biochar after 96 days of incubation.

be short lived because it was not expected to remain for more than a few months in these soils (Novak et al., 2007).

The higher-level biochar amendment (44 tonnes ha^{-1}) had significantly lower PR than the control. And when PR were regressed against the amount of biochar added, they had coefficients of determination of 0.78 taken at 44 days of incubation for the first set of measurements (Fig. 1) and 0.83 for the second set taken at 96 days (Fig. 2), showing a general decrease of soil strength with an increase in biochar. Similar results were seen by Chan et al. (2007) when they measured tensile strength of hard-setting Australian soils amended with biochar of lawn and cotton-field waste pyrolized at 450 °C. The same group (Chan et al., 2008) stated that the biochar properties depended on feedstock and pyrolysis conditions when they saw reductions in soil strength with use of poultry litter biochars pyrolized at 450 °C and 550 °C.

Aggregation and Infiltration

Aggregation was higher for treatments with switchgrass than for those without (Table 1); but it was not different for the biochar-amended treatments, and the interaction between the biochar and switchgrass was not significant at $P < 0.05$. Infiltration effects were not significant for the main effects of infiltration or biochar. When amended treatments (in the interaction) were compared with the nonamended treatment (no switchgrass and no biochar) at $P < 0.10$, infiltration was higher for all but one amended treatment (Table 2). This would be consistent with the findings that a reduction in strength increases infiltration as reported by Wheaton et al. (2008).

TABLE 1. Aggregation of Switchgrass and Biochar Treatments of Ap Horizon of the Norfolk Loamy Sand After 70 Days of Incubation

	Biochar Additions, g kg^{-1}				
	0	5	10	20	Mean
Switchgrass	Aggregation (% on a Weight Basis)				
Yes	13.0	12.7	12.3	11.8	12.5a[a]
No	9.95	9.53	10.7	9.23	9.85[b]
Mean	11.6[ab]	11.1[a]	11.5[a]	10.5[a]	

[a]Means in column with the same letter are not significantly different at $P < 0.05$ using the LSD test.

[b]Means in row with the same letter are not significantly different at $P < 0.05$ using the LSD test.

LSD: least significant difference.

TABLE 2. Infiltration of the Switchgrass and Biochar Treatments in the Ap Horizon of the Norfolk Loamy Sand After 70 Days of Incubation

	Biochar Additions, g kg^{-1}				
	0	5	10	20	Mean
Switchgrass	Infiltration, g min^{-1}				
Yes	19.0[a]	14.8	14.0	16.4	16.0a[b]
No	8.46	21.0	13.1	15.5	14.5a
Mean	13.7a[c]	17.9a	13.5a	16.0a	

[a]Means for the interactions have an LSD of 5.3 at $P < 0.10$.

[b]Means in columns with the same letter are not significantly different at $P < 0.05$ using the LSD test.

[c]Means in rows with the same letter are not significantly different at $P < 0.05$ using the LSD test.

LSD: least significant difference.

Water-Holding Capacity

Water-holding capacity was inferred from the amounts of water that were added to maintain 10% water content and from the total amount of water leached. Water that was added every 2 to 3 days to maintain 10% water content for incubation (excluding infiltration tests) ranged from 376 g to 465 g when the various treatments were averaged over the replicates. Less water was added to the treatments that had switchgrass (Table 3), indicating that the grass-amended soil held more water against gravity and evaporation. This would be consistent with the fact that soils with more OM hold more water. The switchgrass effect was not consistent across all levels of biochar amendment. Water added was significantly less for the switchgrass-amended treatments that had 0 or 44 tonnes ha^{-1} biochar added; the other two treatments were not significantly different. Biochar-amended treatments did not show any significance for amount of water added (Table 3).

Treatments were leached twice during the incubation period, and the leachate was collected. For both leachings, the amounts of leachate collected did not differ for the switchgrass treatments, and they were significantly lower for the highest biochar treatment compared with the control. And although

TABLE 3. Total Amount of Water Added to the Columns to Maintain 10% Soil Water Content During the 70 Days of Incubation

	Biochar Additions, g kg^{-1}				
	0	5	10	20	Mean
Switchgrass	Water Added, g				
Yes	356[a]	382	392	371	375[ab]
No	400	370	376	413	390[b]
Mean	378[ac]	376[a]	384[a]	392[a]	

[a]Means for the interactions have an LSD of 28 at $P < 0.05$.

[b]Means in columns with the same letter are not significantly different at $P < 0.05$ using the LSD test.

[c]Means in rows with the same letter are not significantly different at $P < 0.05$ using the LSD test.

LSD: least significant difference.

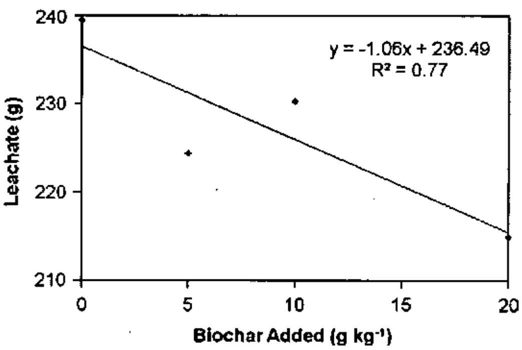

FIG. 3. Plot of the second leachate amount versus biochar amendment averaged over replicated and switchgrass amendments that were not different.

these amounts were not significantly correlated for the first leaching, they were for the second one (Fig. 3), with the increase of biochar correlating 77% with the decrease of leachate. This agrees with what was expected from the literature that reports improvements in soil physical characteristics for biochar amendment. Increased water-holding capacities are anticipated by many researchers (Laird, 2008). The ability to hold water and the amount held will probably differ with feedstock, the method used to turn it into biochar, and the medium to which it was added (Novak et al., 2009b). The apparent contradiction between more water being held at leaching and no difference of water being added to maintain 10% water content can be explained by water held in larger pores. At 10%, larger pores may not be filled, whereas at leaching, they would be filled with loosely held water.

CONCLUSIONS

The ability of switchgrass and biochar to improve soil physical properties had mixed results. Adding switchgrass improved soil PR in the second reading, and it increased the ability of the soil to hold water against evaporation. Improvements caused by switchgrass addition are expected to be short-lived because fresh OM characteristically deteriorates quickly in these soils and climate.

Regressions of biochar and soil PR showed its tendency to reduce soil strength. Biochar also improved soil water content during free drainage. Adding biochar did not improve aggregation or infiltration rate. Because others have reported improvements that we did not see, our results may be a characteristic of the biochar feedstock, pecan shells, or of the way the biochar was produced. Nevertheless, the improvement in PR, water holding, and the C it adds to the soil are expected to be long lasting because of the recalcitrant nature of the biochar. These are encouraging results for southeastern Coastal soils that characteristically have high PR, low water-holding capacities, and low C contents.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Agriculture–Agricultural Research Service under the ARS-GRACEnet project. The authors thank Mr. Don Watts, Ms. Sheeneka Green, and Mr. Dean Evans for laboratory assistance. Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product of the U.S. Department of Agriculture or by North Carolina A&T State University and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

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